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Potential Effects of Episodic Deposition on Nutrients and Heavy Metals in Decomposing Litters of *Suaeda glauca* in Salt Marsh of the Yellow River Estuary, China

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Abstract: Episodic deposition has been recognized as a major factor affecting the decomposition rate of detrital material in salt marshes. In this paper, three one-off burial treatments, no burial treatment (0 cm, NBT), current burial treatment (10 cm, CBT) and strong burial treatment (20 cm, SBT), were designed in intertidal zone of the Yellow River Estuary to determine the potential influences of episodic deposition on nutrient (C, N) and heavy metal (Pb, Cr, Cu, Zn, Ni, Mn, Cd, V and Co) variations in decomposing litters of *Suaeda glauca*. Results showed that although various burial treatments showed no statistical difference in decomposition rate of *S. glauca*, the values generally followed the sequence of CBT (0.002 403/d) > SBT (0.002 195/d) > NBT (0.002 060/d). The nutrients and heavy metals in decomposing litters of the three burial treatments exhibited different variations except for N, Cu, Cr, Ni and Co. Except for Mn, no significant differences in C, N, Pb, Cr, Cu, Zn, Ni, V and Co concentrations occurred among the three treatments ($P > 0.05$). With increasing burial depth, Cr and Cd levels generally increased while Cu, Ni and Mn concentrations decreased. Although episodic deposition was generally favorable for C and N release from *S. glauca*, its influence on release was insignificant. In the three burial treatments, Pb, Cr, Zn, Ni, Mn, V and Co stocks in *S. glauca* generally evidenced the export of metals from litter to environment, and, with increasing burial depth, the export amounts increased greatly. The *S. glauca* were particular efficient in binding Cd and releasing Pb, Cr, Zn, Ni, Mn, V and Co, and, with increasing burial depth, stocks of Cu in decomposing litters generally shifted from release to accumulation. The experiment indicated that the potential eco-toxic risk of Pb, Cr, Zn, Ni, Mn, V and Co exposure would be serious as the strong burial episodes occurred in *S. glauca* marsh.

Keywords: decomposition; nutrient and metal; episodic deposition; *Suaeda glauca*; Yellow River Estuary

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1 Introduction

Salt marshes have long been recognized by their remarkable rates of primary productivity and a substantial part of the annual plant production becomes litter (Bouchard and Lefeuvre, 2000). Litter decomposition rates and associated element dynamics are strongly regulated by internal factors such as the species and their substrate quality (Kok et al., 1990; Akanil and Middleton, 1997) and by external factors, which include biotic factors

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(e.g., microfungi and invertebrates activities) (Hieber and Gessner, 2002; Anesio et al., 2003) and abiotic factors such as flooding regime (Zhao et al., 2014), climate condition (Raija et al., 2004), salinity (Lopes et al., 2011), nutrient status (Xie et al., 2004), pH (Neher et al., 2003), oxygen concentration (Freeman et al., 2004), sedimentation (Vargo et al., 1998) and regional characteristics (Denvard et al., 1999). Among them, episodic deposition has been recognized as a major factor affecting the decomposition rate of detrital material in salt marshes (Vargo et al., 1998). Salt marshes also act as a geochemical trap for nutrients and heavy metals anthropogenically imported into the environment (Hart, 1982). Marsh plants not only can absorb the nutrients and metals imported into salt marshes and adjacent waters (Vandecasteele et al., 2005; Jia et al., 2018), but also can release them as they decay (Baldantoni et al., 2004). Decomposing detritus may be a sink of metals if, during decomposition, metals could be bound to the litter by passive sorption onto organic surfaces or by physiological mechanism of microbial colonizers. Plant detritus can also act as a metal source as microbial activity mobilizes metals or as it becomes available to deposit feeders (Weis and Weis, 2004). Particularly, the consumption of detritus that contained metals can cause metal accumulation and toxic effects in higher trophic levels (Zhang et al., 2010).

Considerable efforts have been conducted to explore the litter decomposition in estuarine marshes (Du Laing et al., 2006; Menéndez and Sanmartí, 2007; Connolly et al., 2014; Janousek et al., 2017), salt marshes (Quintino et al., 2009; Lopes et al., 2011; Simões et al., 2011; Jones et al., 2016), mangrove swamps (Sánchez-Andrés et al., 2010; Gladstone-Gallagher et al., 2014; Hossain et al., 2014; Keuskamp et al., 2015; Nordhaus et al., 2017), and coastal lagoons (Menéndez, 2009; Costantini et al., 2009; Bertoli et al., 2016). Most of these studies focus on exploring litter decomposition rates and nutrient variations in decomposing litters and the roles of abiotic and biotic factors on decomposition, whereas information on the influences of sediment disturbance on litter decomposition remains scarce. In addition, few studies investigate the variations of heavy metal in decomposing litters in salt marshes (Du Laing et al., 2006; Pereira et al., 2007; Sun et al. 2016). Particularly, information on the effects of episodic deposition on metal variation and accumulation in decomposing litters is still lacking. In China, the related studies mainly focus on mangrove swamps (Huang et al., 2001; Sheng, 2009; Zhou et al., 2012; Chen, 2013; Li and Ye, 2014) and coastal/estuarine marshes (Chen, 2008; Tong et al., 2011; Guan, 2013; Shao et al., 2014; Zhang et al., 2014; Li et al., 2016) in the tropical and subtropical regions, while information on the salt marshes in warm temperate regions remains scarce. Moreover, present studies mainly focus on litter decomposition and its related affecting factors, whereas information on heavy metal variations in decomposing litters as affected by episodic deposition is still very limited.

The Yellow River, located in warm temperate region, is the second largest river in China, and approximately 1.06×10^8 t of sediment (average value during 2007–2018) is carried to the estuary and deposited in the slow flowing landform every year, resulting in vast floodplain and special marsh landscape (Xu et al., 2002). The deposition rate of sediment in the Yellow River not only affects the formation of salt marsh, but also influences the water or salinity gradients and the succession of plants from the land to the sea. The widths of intertidal zone in the Yellow River Estuary range from 4 km to > 10 km, and, in a seaward direction, *Suaeda glauca* are widely distributed. As a prevalent plant in salt marshes of the Yellow River Estuary, it is often affected by the deposition of tide physical disturbance and bioturbation. It was reported that the annual runoff of the Yellow River showed great inter-annual changes since the 1980s. The runoff reached the maximum of 49.1 billion m^3 in 1983 and then decreased and fluctuated at 20.0 billion m^3 in the following several years. From 1997 to 2002, the annual runoff was below 10.0 billion m^3 (Cui et al., 2009). The low flows of the Yellow River led to a significant decrease in freshwater supply to the estuary. In order to increase the supply of freshwater and sediment for the Yellow River Estuary and to alleviate the sedimentation of Xiaolangdi Reservoir and riverbed, the 'flow-sediment regulation project' (FSRP) was initiated by the nation in 2002. During the implementation of the FSRP, the freshwater in the Xiaolangdi Reservoir and the sediment in reservoir and riverbed are discharged into the Yellow River Estuary within approximately 20 d, and accompanying with river/tide flooding, the litters in *S. glauca* marsh can be directly buried within the sediment to a considerable thick in a very short time, which may affect litter decomposition and nutrient/metal levels in decomposing litters. However, little is known about the impacts of episodic deposition on nutrient and metal stocks in *S. glauca* marsh of the Yellow River Estuary.

In this paper, the influence of episodic deposition on nutrient (C, N) and heavy metal (Pb, Cr, Cu, Zn, Ni, Mn, Cd, V and Co) concentrations in decomposing litters of *S. glauca* were investigated. It is hypothesized that the decomposition rates and nutrient/metal levels differed among burial treatments, which would have great effects on the ecological functions of *S. glauca* marsh. Objectives of this study were: 1) to investigate whether episodic deposition would have great effects on decomposition of *S. glauca*, 2) to determine the variations of nutrient and metal in decomposing litters as affected by different burial disturbances, and 3) to determine the potential impacts of episodic deposition on nutrient and metal stocks in decomposing litters.

2 Materials and Methods

2.1 Study region

This study was carried out in intertidal zone of the northern Yellow River Estuary, located in the Nature Reserve of Yellow River Delta (37°35′N–38°12′N, 118°33′E–119°20′E) in Dongying City, Shandong Province, China (Fig. 1). The nature reserve is of typical continental monsoon climate with distinctive seasons. The average temperatures in spring, summer, autumn and winter are 10.7℃, 27.3℃, 13.1℃ and –5.2℃, respectively. Annual evaporation is 1962 mm and annual precipitation is 551.6 mm, with about 70% of precipitation occurring between June and August. The tide in intertidal zone is irregular semidiurnal tide and the mean tidal range is 0.73–1.77 m (Li et al., 1991). The soils in the study region are dominated by saline soil and the main vegetations include *Pragmites australis*, *Suaeda salsa*, *S. glauca*, *Triarrhena sacchariflora* and *Tamarix chinensis*. The sequence of geomorphic units is complete in intertidal zone of the Yellow River Estuary, which generally comprises three areas in a seaward direction: high marsh, middle marsh and low marsh. As a prevalent plant in low marsh, *S. glauca* is often affected by the sedimentation of tidal disturbance, bioturbation and Yellow River flooding during the implementation of the FSRP. Every year, the FSRP was carried out in the last ten-day of June and ended in the first ten-day of July (only lasted 20 d), and in such a short period, the river/tide water frequently flooded the salt marshes near the estuary and resulted in considerable deposition (approximately 5–6 cm thick) (Mou, 2010). It was reported that the sedimentary rate in *S. glauca* marsh approximated 9–10 cm/yr and about 6–7 cm was observed due to the significant influences of both tidally induced sedimentation and FSRP (Mou, 2010). The experimental plot was laid in the above-mentioned low marsh and three sub-plots were laid in it along the contour line (with the similar elevation).

2.2 Experimental methods

2.2.1 In situ decomposition experiment

The standing litters were collected from *S. glauca* community on 20 March 2008. Each 20 cm × 20 cm litterbag was made of nylon netting (0.5 mm mesh) and

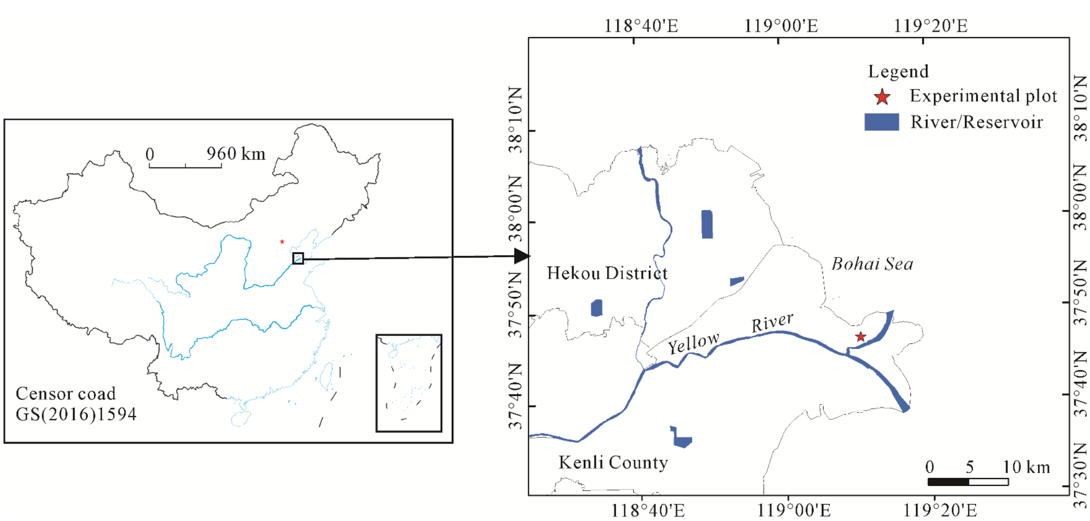

Fig. 1 Sketch of the Yellow River Estuary and the experimental plots

filled with 15 g litter (dried weight). To investigate the potential effects of episodic deposition on decomposition rate and nutrient/metal levels of *S. glauca*, three one-off burial treatments (no burial treatment (NBT), current burial treatment (CBT) and strong burial treatment (SBT)) were designed in each sub-plot. The litterbags were artificially buried to the depths of 0, 10 and 20 cm on 21 April 2008 to simulate the NBT, CBT and SBT treatments, respectively. In order to prevent the litterbags from being influenced by burial disturbance during decomposition, each sub-plot was tightly enclosed by nylon netting (0.25 mm mesh, 1.5 m height).

The bulk density of sediment used in the experiment is (1.64 ± 0.03) g/cm and presents silty clay texture, with (11.62 ± 2.09)% of clay, (65.11 ± 11.29)% of silt and (23.28 ± 13.39)% of sand. The sediment shows low organic matter and total nitrogen contents, with the values of (0.94 ± 0.01)% and (0.79 ± 0.06) mg/g, respectively. The pH and electrical conductivity (EC) of the sediment are (8.86 ± 0.04) and (18.07 ± 0.43) mS/cm, respectively. The concentrations of Pb, Cr, Cu, Zn, Ni, Mn, V and Co in sediment are (51.75 ± 8.17), (47.62 ± 10.37), (28.22 ± 1.00), (64.82 ± 5.37), (27.18 ± 1.51), (556.01 ± 10.44), (106.32 ± 4.03) and (14.63 ± 0.98) mg/kg, respectively.

The *in situ* decomposition experiment included nine sampling periods with different intervals (2008-07-11 (80 d), 2008-08-09 (109 d), 2008-09-20 (151 d), 2008-10-20 (181 d), 2008-11-15 (207 d), 2009-04-26 (371 d), 2009-06-25 (431 d), 2009-08-25 (492 d) and 2009-11-12 (571 d)), and, on each sampling date, four litterbags for each treatment were retrieved from each sub-plot, with 36 litterbags in total. A total of 324 litterbags were collected throughout the experiment. After retrieval, these litterbags were immediately taken back to the laboratory and the lichen, sediment and macro-invertebrates in litterbags were removed. All litterbags were further cleaned gently and weighed after being dried.

2.2.2 Environmental variables

Sediment temperatures (0, 10 and 20 cm) were measured by geothermometer in the three sub-plots on each sampling date. Sediment moisture, electrical conductivity (EC) and pH in 0, 10 and 20 cm depths were measured by high-precision moisture measuring instrument (AZS-2), Soil & Solution EC meter (Field Scout) and portable pH meter (IQ150), respectively.

2.2.3 Sample determinations

Sediment organic matter was determined by $K_2Cr_2O_7$ oxidation method and sediment grain-size was measured by the Coulter Laser granulometer. The samples of decomposing litter and sediment were analyzed for total carbon (TC) and total nitrogen (TN) concentrations by element analyzer (Elementar Vario Micro, German). A 0.1000 g homogenized sediment sub-sample was digested with 2 mL HNO_3, 1 mL $HClO_4$ and 5 mL HF at 160℃–190℃ for 16 h. The residue was dissolved in 2 mL of 4 mol/L HCl and then diluted to 10 mL with deionized water for heavy metal analysis. A 0.2000 g plant sub-sample was digested in a mixture of 65% HNO_3 (2 mL) and 30% H_2O_2 (1 mL). The residue was diluted with deionized water to 10 mL for analyzing heavy metal concentrations. The levels of Pb, Cr, Cu, Zn, Ni, Mn, Cd, V and Co in all samples were determined by Agilent 7500 ICP-MS (Inductively coupled plasma mass spectrometry, Agilent Company, America). Quality assurance and quality control were assessed using duplicates (three replications), method blanks and standard reference materials (GBW07401 and GBW08513) from the National Research Center for Standards in China with each batch of samples (one blank and one standard for each 20 samples).

2.2.4 Parameter calculations

Litter mass loss (R, %) and decomposition rate (W_t, /d) were calculated by the following equations (Olson, 1963):

$$R = \left[\left(W_0 - W_t\right)/W_0\right] \times 100\% \tag{1}$$

$$W_t = W_0 e^{-kt} \tag{2}$$

where W_0 is the original dry mass (g), W_t is the dry mass at time t (g), k is the decay constant, and t is decomposition time (d).

The accumulation index of the i element (C, N, Pb, Cr, Cu, Zn, Ni, Mn, Cd, V and Co) (AI_i) was used to express its accumulation or release during litter decomposition (Sun and Mou, 2016):

$$AI_i = \frac{DM_j \times C_j}{DM_0 \times C_0} \times 100\% \tag{3}$$

where DM_0 is the original dry mass (g), C_0 is the original element concentration (mg/kg), DM_j is the dry mass at time j (g), and C_j is the element concentration in litter at time j (mg/kg). AI > 100% indicated net element accumulation, whereas AI < 100% indicated net element release.

The metal/carbon ratio (M_t/C_t) was calculated by the metal and carbon concentrations at time t.

2.2.5 *Statistical analysis*

The samples were presented as means over the replications, with standard deviation (SD). The Shapiro-Wilk test was applied to identify the normality of data before the related statistical analyses were conducted. Pearson correlation analyses were used to examine the relationships between temperatures and mass losses and between element concentrations and C/M ratios (or C/N ratios). The analysis of variance (ANOVA) tests (SPSS for windows 11.0) was employed to determine if mass losses, environmental variables, decomposition rates and element concentrations among the three burial treatments differed significantly ($P < 0.05$). If ANOVA showed significant differences, multiple comparison of means was undertaken by Tukey's test with a significance level of $P = 0.05$.

3 Results

3.1 Mass loss and decomposition rate

The mass losses of *S. glauca* in the three burial treatments generally increased, but no significant differences were observed among them ($P > 0.05$) (Fig. 2a). At the end of decomposition, the mean percent of mass remaining in the NBT, CBT and SBT treatments were 23.00%, 23.17% and 23.42%, respectively. Although burial treatments showed no statistical difference in decomposition rate of *S. glauca*, the values generally followed the sequence of CBT (0.002 403/d) > SBT (0.002 195/d) > NBT (0.002 060/d). Moreover, higher $t_{0.95}$ (time needed for 95% of dry mass decomposed) was observed for the NBT treatment (3.65 yr) compared to the SBT (3.42 yr) and CBT (3.12 yr) treatments (Fig. 2b).

3.2 Nutrient and metal concentrations

The C concentrations in *S. glauca* fluctuated greatly and varied between 37.02% and 44.64% for NBT, from 37.32% to 43.61% for CBT and from 37.32% to 42.68% for SBT, respectively (Fig. 3a), whereas the N concentrations in the three treatments generally demonstrated increasing tendency (Fig. 3b). Heavy metal concentrations in the three burial treatments exhibited similar variations during decomposition except for Pb, Zn, Mn and V, and, particularly, Cu levels in the three treatments showed increasing tendency. With increasing burial depth, Cr and Cd concentrations generally increased while Cu, Ni and Mn levels generally decreased (Fig. 4). Except for Mn, no significant differences in C, N, Pb, Cr, Cu, Zn, Ni, V and Co concentrations were observed among the three burial treatments ($P > 0.05$).

3.3 Nutrient and metal stocks

The AI_C and AI_N variations of *S. glauca* in the three burial treatments were similar, and, with increasing burial depth, no statistical difference in AI_C or AI_N was observed. Even so, episodic deposition treatments were generally favorable for C and N release (Fig. 5). In the three treatments, Pb, Cr, Zn, Ni, Mn, V and Co stocks in *S. glauca* generally evidenced the export of metals from litter to environment, and, with increasing burial depth, the export amounts increased greatly (Fig. 6). Stocks of Cd in *S. glauca* in the CBT and SBT treatments were generally positive, evidencing incorporation of the metal in most sampling times. With increasing burial depth, stocks of Cu in *S. glauca* shifted from release to accumulation in most periods (Fig. 6).

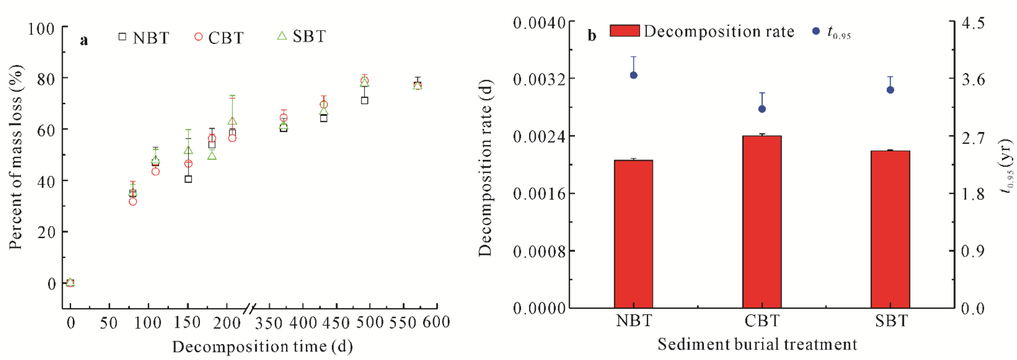

Fig. 2 Percent of mass loss (a), and decomposition rate and $t_{0.95}$ (time needed for 95% of dry mass decomposed) (b) of *Suaeda glauca* in different burial treatments during decomposition. NBT, no burial treatment; CBT, current burial treatment; and SBT, strong burial treatment.

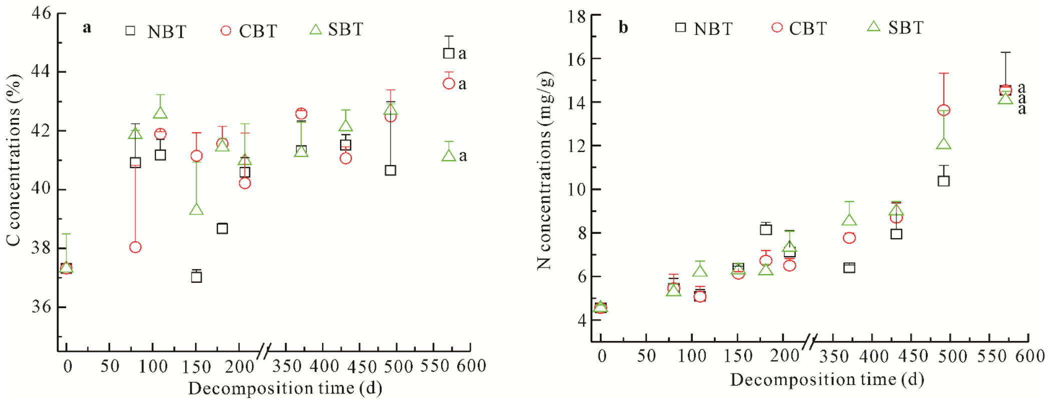

Fig. 3 Variations of C (a) and N (b) concentrations in *Suaeda glauca* of different burial treatments during decomposition. Values with the same letters are not significantly different at $P < 0.05$. NBT, no burial treatment; CBT, current burial treatment; and SBT, strong burial treatment.

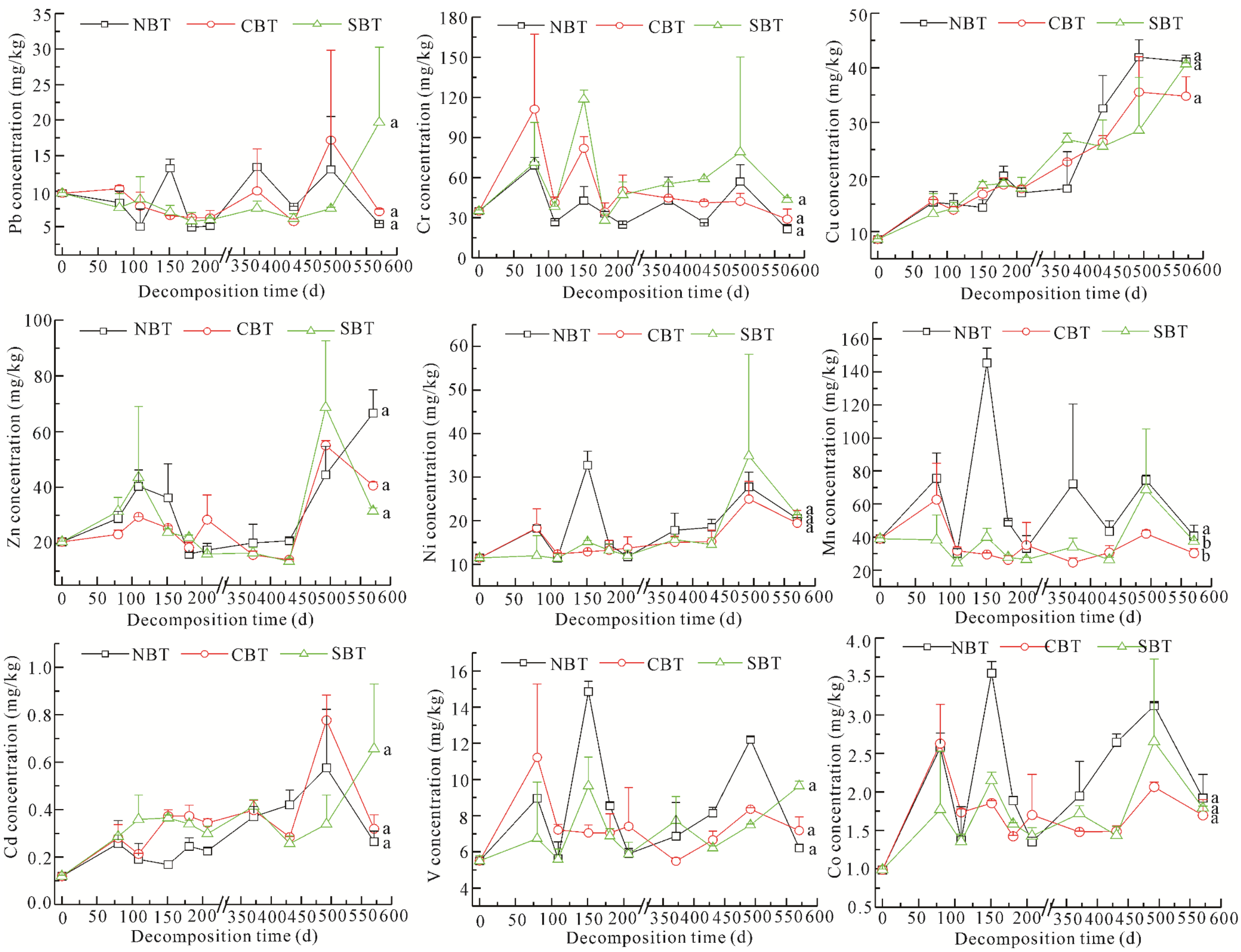

Fig. 4 Variations of heavy metal concentrations (mg/kg dry mass) in *Suaeda glauca* of different burial treatments during decomposition. NBT, no burial treatment; CBT, current burial treatment; and SBT, strong burial treatment; Values with the same letters are not significantly different at $P < 0.05$.

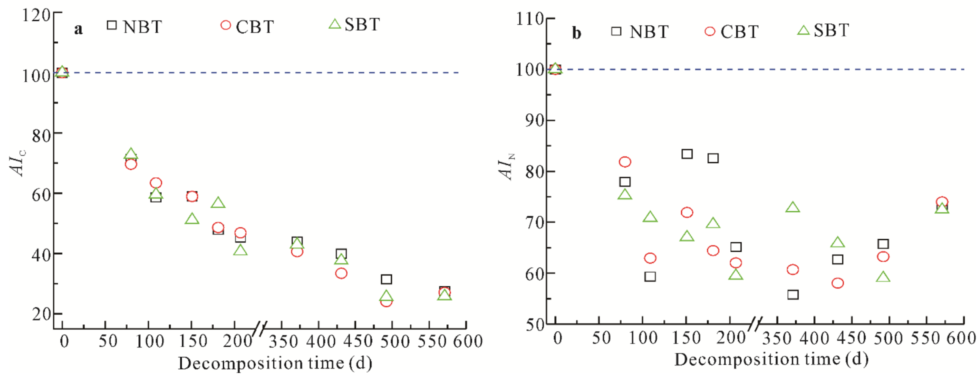

Fig. 5 Variations of C (a) and N (b) stocks in *Suaeda glauca* of different burial treatments during decomposition. NBT, no burial treatment; CBT, current burial treatment; and SBT, strong burial treatment. AI_C, the accumulation index of C; and AI_N, the accumulation index of N.

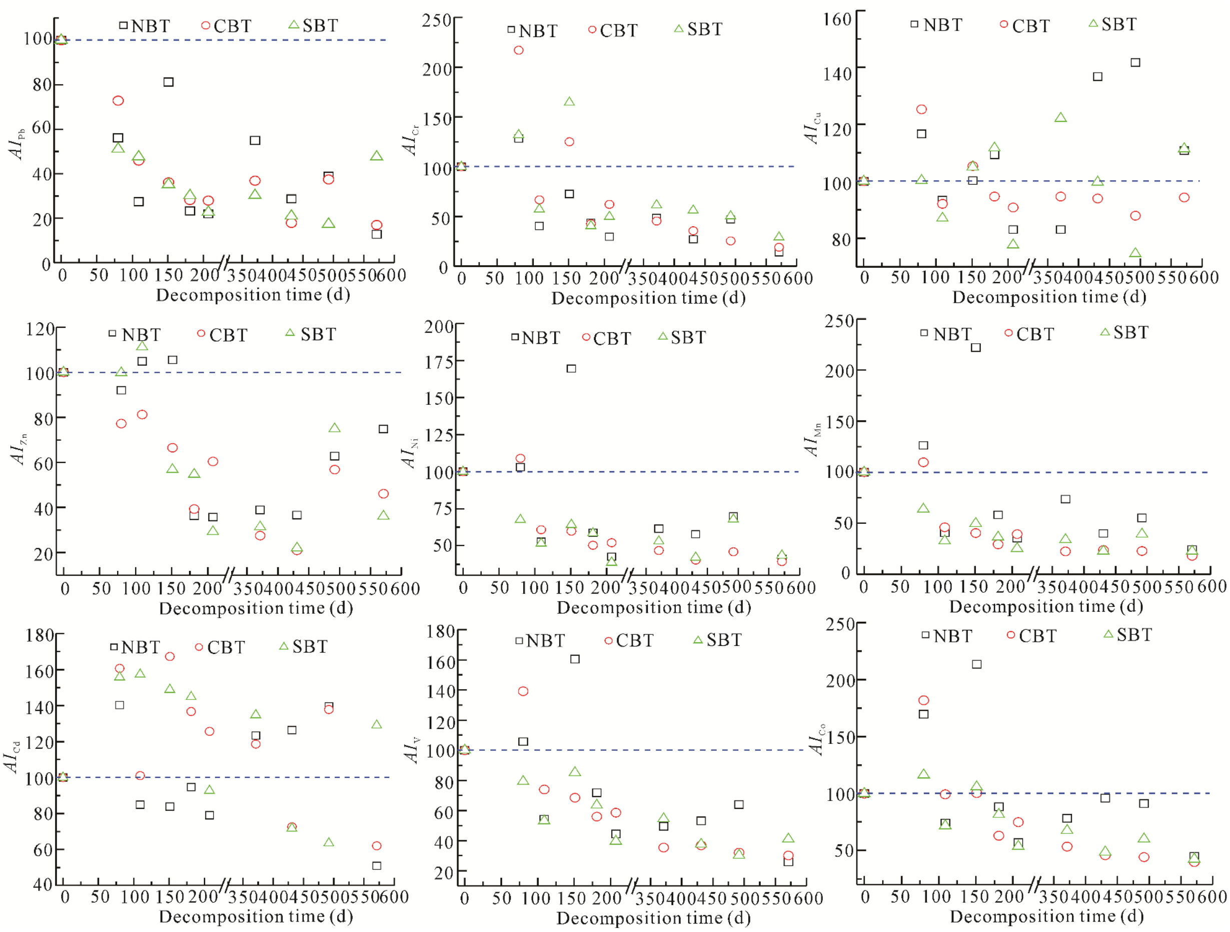

Fig. 6 Variations of Pb, Cr, Cu, Zn, Ni, Mn, V and Co stocks in *Suaeda glauca* of different burial treatments during decomposition. NBT, no burial treatment; CBT, current burial treatment; and SBT, strong burial treatment. AI_i, the accumulation index of the element i (Pb, Cr, Cu, Zn, Ni, Mn, Cd, V and Co)

4 Discussion

4.1 Effects of episodic deposition on decomposition rate of decomposing litters

It was hypothesized that the decomposition rate of *S. glauca* differed among the three burial treatments and this was partly tested in this investigation. Although burial treatments showed no statistical difference in decomposition rate of *S. glauca*, higher values generally occurred in the CBT and SBT treatments (increased by 6.55%–16.65% compared to the NBT treatment) (Fig. 2b). Similar results were reported by Sun and Mou (2016) and Wei et al. (2017) who found that sediment deposition stimulated the decomposition rates of *Phragmites australis*, *Flaveria bidentis* and *Setaria viridis* (Table 1). However, Vargo *et al*. (1998), Gladstone-Gallagher et al. (2014) and Cao et al. (2016) implied that sediment deposition significantly inhibited the decomposition of detritus via a series of direct and indirect mechanisms such as compaction of detritus, reduction of gas (O_2 and CO_2) exchange between the detrital layer and the surrounding, and suppression of bacterial and fungal breakdown of detritus. Wang et al. (1994) even indicated that burial by sediment led to an initial decline in rate of cattail (*Typha glauca*) litter decay, for two months, but thereafter, rates for buried and unburied litter were similar (Table 1). Previous studies have indicated that litter quality clearly affected decomposition rate and C/N ratio was often used as predictor of decomposition rate; a high ratio generally resulted in a slow decomposition rate (Harmon et al., 1990; Hobbic, 1996). In this experiment, the C/N ratios of *S. glauca* in the buried treatments (CBT and SBT) during decomposition were slightly lower than those in the unburied treatment (NBT) (Fig. 7), which could partly explain the slightly higher decomposition rates in the burial treatments.

The primary environmental factors might also affect the decomposition rates of *S. glauca* in the three burial treatments. It was reported that the anoxic degradation of detritus was independence of temperature (Sun et al., 1993) and this was tested in this study. Although the average temperatures differed by up to 1.10℃ and 3.49℃ between NBT and CBT and between CBT and SBT, respectively (Table 2), significant correlations between temperatures and decomposition rates were not observed ($P > 0.05$). Moreover, no significant difference in sediment pH occurred among the three treatments (Table 2), indicating that it might be less important in contributing to the observed difference in decomposition rates. By comparison, sediment moisture and EC were significantly different among the three treatments ($P < 0.05$), and, with increasing burial depth, the former generally increased while the latter generally decreased (Table 2). Previous studies have found that salinity might have either positive, negative or even no effect on decomposition (Table 3). In this experiment, the inverse relationships between salinity (represented by EC) and decomposition rate were observed and higher

Table 1 Comparisons of sediment deposition on litter decomposition rates in different marshes

Marshes	Study regions	Vegetations	Depth (cm)	Effects	References
Freshwater marsh	Unnamed lake,Washtenaw County, Michigan, US	*Typha latifolia*	0.2 [a]	–	Vargo et al. (1998)
		Typha angustifoliam,	1.2 [b]	–	
		Sparganium eurycarpum	1.2 [b]	–	
	Liangzi Lake, Ezhou, Hubei Provionce, China	*Vallisneria natans*	0, 5	–	Cao et al. (2016)
		Potamogeton maackianus	0, 5	–	
	Tuanbo Lake, Jinhai, Tianjin, China	*Flaveria bidentis*	0, 15	+	Wei et al. (2017)
		Setaria viridis	0, 15	+	
Mangrove swamp	Whangamata Harbour, New Zealand	*Avicennia marina*	0, 40	–	Gladstone-Gallagher et al. (2014)
Prairie marsh	Des Plaines River, Wadsworth, Illinois, US	*Typha glauca*	0, 1, 2, 4	0	Wang et al. (1994)
Salt marsh	Yellow River Estuary, China	*Phragmites australis*	0, 10, 20	+	Sun and Mou (2016)
		Suaeda glauca	0, 10, 20	+	This study

Notes: '+', positive effect; '–', negative effect; and '0', no effect. [a] One-time sediment application, multiple sediment application and no sediment application; and [b] P-enriched sediment application, un-enriched sediment application and no sediment application.

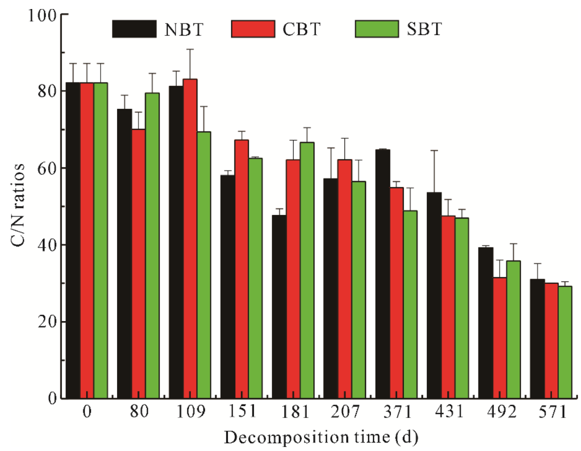

Fig. 7 Variations of C/N ratios in *Suaeda glauca* of different burial treatments during decomposition. NBT, no burial treatment; CBT, current burial treatment; and SBT, strong burial treatment

decomposition rate generally occurred in the CBT and SBT treatments (low salinity). The reason was that, with increasing salinity, the enzymatic activity on decomposing litters and the amounts of microorganism generally decreased and the activities of some microbes might be prohibited or even disappeared (Roache et al., 2006; Chen and Shi, 2010), which was unfavorable for litter decomposition. Although the EC in the NBT treatment was significantly higher than those in the buried treatments (Table 2), the decomposition rate of *S. glauca* in the NBT treatment, compared to the CBT and SBT treatments, did not decreased greatly (Fig. 2b). The influence of salinity on decomposition of *S. glauca* in the NBT treatment was very likely mediated by microorganisms adapted to hyper-saline conditions. Wang et al. (2009) found that although significantly negative relationship occurred between salinity and microorganism amount in surface sediments of salt marsh in the Yellow River Delta, some microorganisms adapted to saline conditions still could be observed, and, particularly, the amounts of halophilic bacteria were much higher than those of actinomyoetes and fungi. Similar result was reported by Lopes et al. (2011) who found that higher decomposition rate of *Fucus vesiculosus* was generally observed in the areas of higher salinity and this could be better explained by the adaptation of microorganisms acting to saline conditions. Significant difference in sediment moisture were also observed among the three burial treatments ($P < 0.05$), and, with increasing burial depth, the moisture increased greatly (Table 2). It was found that, with increasing moisture, the O_2 in litter could be depleted rapidly and the metabolism of decomposition microbes would be restrained (Laiho et al., 2004; Freeman et al., 2004). However, Webster and Benfield (1986) implied that the impacts of anaerobiosis on decomposition rate were not always inhibitory. As the litter was buried, the anaerobic conditions formed in different burial depths might have either positive (Sun and Mou, 2016), negative (Benner et al., 1984) or even no effect (Kristensen and Blackburn, 1987) on decomposition. In this investigation, the positive effects of CBT and SBT treatments on decomposition of *S. glauca* were very likely ascribed to the maintenance of adequate moisture for microbial/fungal colonization and activity (Mendelssohn et al., 1999). The higher activities of microbes in burial treatments could also be verified by the lower salinity in the CBT and SBT treatments and the relative lower C/N ratios of *S. glauca* in the SBT treatment as mentioned above.

It was found that the macrobenthos such as *Portunus trituberculatus*, *Tritodynamia rathbunae*, *Macrophthalmus dilatum* and *Macrophthalmus japonicus* were prevalently distributed in intertidal zone of the Yellow River Estuary (Leng et al., 2013). Particularly, the biomass and habitat density of macrobenthos in *S. glauca* marsh (low marsh) were very high and the values reached 431.23, 239.13 g/m^2 and 1013.79, 725.06 ind/m^2 during spring and autumn (Li, 2011). Thus, the activities of prevalent macrobenthos were very likely affect the decomposition rates of *S. glauca* in burial treatments..

Table 2 Environmental variables in different burial treatments during decomposition

Burial treatments	Sediment temperature (℃)	Sediment moisture (cm^3/cm^3)	EC (mS/cm)	pH
NBT	23.15±12.13^a	0.363±0.161^a	18.07±0.43^a	7.75±0.06^a
CBT	22.05±9.45^a	0.467±0.087^b	7.85±0.75^b	7.68±0.05^a
SBT	18.56±8.15^a	0.451±0.011^b	6.96±0.84^b	8.28±0.12^a

Notes: NBT, no burial treatment; CBT, current burial treatment; and SBT, strong burial treatment. Different letters within the same column indicate significant differences at $P < 0.05$.

Sun et al. (2015) also reported that the vertical depth of macro-invertebrates caves in low marsh was about 10–20 cm, and, in these depths, the horizontal or slop habitats were generally established. Frequent disturbances of macrobenthos in low marsh could improve the gas exchange between the litters in 10–20 cm depth and the surrounding, which might stimulate the decomposition of *S. glauca* in the buried treatments (CBT and SBT). In addition, compared to the CBT treatment, the decomposition rate of *S. glauca* in the SBT treatment was slight lower, which might be related to the weak inhibitory on decomposition caused by the deficiency of O_2 in 20 cm depth.

Table 3 Comparisons of salinity on litter decomposition rates in different marshes

Study regions	Marshes	Vegetation	Salinity (‰)	Effects	References
Yellow River Estuary, China	Salt marsh	*Suaeda glauca*	6.96–18.07[a]	+	This study
Waccamaw River & Savannah River, U.S	Tidal freshwater forested wetland	*Taxodium distichum*	0–0.1, 0.5–2.1, 1.7–3.9, 3.3–4.7	–	Stagg et al. (2017)
		Nyssa aquatica	0–0.1, 0.5–2.1, 1.7–3.9, 3.3–4.7	–	
		Nyssa biflora	0–0.1, 0.5–2.1, 1.7–3.9, 3.3–4.7	–	
	Oligohaline marsh	*Spartina cynosuroides*	0–0.1, 0.5–2.1, 1.7–3.9, 3.3–4.7	+	
		Schoenoplectus robustus *Typha latifolia*	0–0.1, 0.5–2.1, 1.7–3.9, 3.3–4.7	+	
		Zizaniopsis miliacea	0–0.1, 0.5–2.1, 1.7–3.9, 3.3–4.7	+	
Gippsland Lakes, Australia	Freshwater wetland	*Triglochin procerum*	0, 3.5, 7.0, 17.5, 28.0	–	Roache et al. (2006)
Mira Channel, Ria de Aveiro, Western Portugal	Estuarine marsh	*Phragmites australis*	0–38	–	Quintino et al. (2009)
			0–38	–	Lopes et al. (2011)
		Fucus vesiculosus	0–38	+	
Hudson River Estuary, U.S.	Tidal freshwater wetland	*P. australis*	0, 5, 10, 15, 20	0	Connolly et al. (2014)
Northern Jutland, Denmark	Salt marsh	*P. australis*	NA	–[b] +[c]	Mendelssohn et al. (1999)
Sapelo River Estuary, U.S.	Tidal marshes	*Spartina alterniflora*	12–15, 25–29, 28–32	+	Craft (2007)
Doboy Sound Estuary, U.S.		*S. alterniflora*	20–25, 22–25, 25–29	+	
Altamaha River Estuary, U.S.		*S. alterniflora*	0–0.3, 2–6, 14–19	+	
		Spartina cynosuroides	0–0.3, 2–6, 14–19	+	
		Juncus roemerianus Zizaniopsis milaceae	0–0.3, 2–6, 14–19	+	
NA	Freshwater marsh (stream)	*Anguillospora filiformis*	0, 2, 4, 8, 16	–	Canhoto et al. (2017)
		Clavariopsis aquatica	0, 2, 4, 8, 16	–	
		Flagellospora curta	0, 2, 4, 8, 16	–	
		Heliscus lugdunensis	0, 2, 4, 8, 16	–	
		Lemonniera pseudofloscula	0, 2, 4, 8, 16	–	
		Tetrachaetum elegans	0, 2, 4, 8, 16	–	
		Tetracladium marchalianum	0, 2, 4, 8, 16	–	
		Tricladium chaetocladium	0, 2, 4, 8, 16	–	
		Articulospora tetracladia	0, 2, 4, 8, 16	+	
Min River Estuary, China	Salt marsh	*S. alterniflora*	0, 10, 15, 30	–	Hou et al. (2017)
		Cyperus malaccensis	0, 5, 10, 15	–	Hu et al. (2017)
Jiulongjiang River Estuary, China	Mangrove swamp	*Kandelia candel*	0, 10, 25, 35	–	Hu et al. (2010)

Notes: '+', positive effect; '–', negative effect; and '0', no effect. [a] without salinity data, represented by EC; [b] negative effect were observed at low and middle salinity; [c] positive effect occurred at high salinity; and NA, not available.

4.2 Effects of deposition on element level and stock in decomposing litters

The investigation found that the concentrations of C in *S. glauca* in the three treatments fluctuated greatly while those of N generally showed increasing tendency. Gessner (2001) indicated that the nutrient dynamics in decomposing litter was mainly regulated by the C/N ratios in litter and the N availability in decomposition environment (Berg, 1986; Köchy and Wilson, 1997). In this paper, significantly negative correlations were observed between C/N ratios and N concentrations in the NBT (R = –0.919), CBT (R = –0.956) and SBT (R = –0.961) treatments (P < 0.01). Except for CBT treatment (R = –0.665, P < 0.05), no significant correlations occurred between C/N ratios and C concentrations. These implied that the N variations in the three burial treatments might be controlled by C/N ratios while the C variations might be more subjected to EC, sediment moisture and the activities of microorganisms and macrobenthos as mentioned above.

In this experiment, increasing of N concentration in *S. glauca* in the three burial treatments might be attributed to the N immobilization by microbes from sediment or seawater since the salt marsh in the Yellow River Estuary was very limited by N (Cao et al., 2015). Similar results were reported by Gessner (2000) and Sun et al. (2012) who found that the increase of N concentration in decomposing litters of *P. australis* and *Calamagrostis angustifolia* during decomposition was mainly related to the external biological immobilization from decomposition environment (marsh water). In addition, although no significant differences in N concentrations were observed among the three burial treatments, the values in the buried treatments (CBT and SBT) were generally higher than those in the unburied treatment (NBT) (Fig. 3b). Higher N concentrations occurred in burial treatments might rest with two reasons. First, although the litterbags in the NBT treatment were placed in close contact with sediment, the chance of infiltration of sediment particles into the litterbags were much lower compared to the CBT and SBT treatments. Second, during decomposition, significantly higher sediment moisture were observed in the CBT and SBT treatments compared to the NBT treatment (Table 2), which probably increased the chance of N in porewater immobilized by microbes.

The experiment also indicated that the AI_C and AI_N values slightly decreased with increasing burial depth, indicating that burial treatments were generally favorable for C and N release (Fig. 5). The differences in C and N release patterns of the three burial treatments were mainly dependent on the variations of C/N ratios during decomposition. As mentioned above, the C/N ratios of *S. glauca* in the SBT treatment were slightly lower than those in the NBT treatments (Fig. 7), implying that, compared to the NBT treatment, the release amounts of superfluous N in burial treatment might be slightly enhanced. Similar with decomposition rate, the C or N release from *S. glauca* in the CBT and SBT treatments were approximated, implying that the strong burial episodes occurred in *S. glauca* marsh in future would have little effect on C or N release from decomposing litters.

The experiment indicated that the levels of Cu in decomposing litters in the three treatments generally presented increasing tendency (Fig. 4). Similar result was reported by Sun and Mou (2016) who found increasing Cu, Ni and Zn concentrations in decomposing litters of *Phragmites australis* as affected by different sediment burials. In this investigation, increasing of metal levels in decomposing litters might be attributed to passive sorption onto recalcitrant organic fractions and active accumulation by microbial colonizers (Gadd, 1993; Zawislanski et al., 2001). In the process of decomposition, the proportions of recalcitrant organic fractions in different burial treatments significantly increased. Accompanying with tidal wave action, the chance of physicochemical sorption of some metals (e.g., Cu, Pb and Cd) in seawater, suspended particle or sediment onto the remaining recalcitrant organic fractions might be greatly enhanced. Comparatively, the risks of fine particles into litterbags in the CBT and SBT treatments were much higher than that in the NBT though the surface sediment could be easily re-suspended by tidal wave action, which, to some extent, increased the three metal levels in decomposing litters. It was also reported that C/N ratio was an effective index in representing decomposition rate and microbial activity (Harmon et al., 1990; Hobbic, 1996). In this experiment, the C/N ratios of *S. glauca* in the three burial treatments during decomposition generally decreased (Fig. 7), indicating that the activities of microbes in decomposing litters might be greatly enhanced and this might increase the active accumulation of some metals (e.g., Cu, Pb and Cd) by microorganisms. The conclusion could be partly verified by Pearson correlation analyses which showed that significantly negative correlations occurred between Cu concentrations and C/N ratios in the three burial treatments ($P < 0.01$), and between Cd levels and C/N ratios in the CBT and SBT treatments ($P < 0.05$) (Table 4). The above speculation could also be tested by Windham et al. (2004) and Du et al. (2006) who found that microbial action was likely an important mechanism responsible for the metal enrichment and an involvement of fungal activity occurred in metal accumulation by direct incorporation in fungal biomass and enhanced binding of metals to the decomposition litter and by induced changes in litter quality by mineralization.

The experiment implied that, during decomposition, Pb, Zn, Mn and V concentrations in the three burial treatments exhibited different variations while Cu, Cr, Ni and Co levels showed similar variations. Fluctuations of these metals in *S. glauca* of different treatments not only depended on the complex interactions of above factors but also rested with M/C ratios. Once carbon (C) was the primary constituent of decomposing litter, metal level could be normalized to C content to better interpret the variation of metal levels as litter decomposed (Pereira et al., 2007). In this study, significantly positive correlations occurred between metal concentrations (Pb, Cr, Cu, Zn, Ni, Mn, V and Co) and M/C ratios in the three burial treatments ($P < 0.01$) (Table 4), indicating that M/C ratio might be one of important factors controlling the metal variations in *S. glauca* in different burial treatments. Besides M/C ratio, the variations of some metal concentrations (Cu, Cd and Ni) in the burial treatments were also affected by C/N ratios since significantly negative correlations were observed between the three metal levels and C/N ratios ($P < 0.01$ or $P < 0.05$) (Table 4), implying that both physicochemical sorption of dissolved metals onto recalcitrant organic fractions and active accumulation by microorganisms might be important processes influencing the variations of the three metal levels during decomposition.

The experiment also found that Cr and Cd concentrations in decomposing litters generally increased with increasing burial depth (Fig. 4). For one thing, the chance of infiltration of fine particles into decomposing litters in the CBT and SBT treatments was much higher than that in the NBT treatment, which might increase metal levels (e.g., Cr and Cd) in *S. glauca*. For another, significantly higher moisture occurred in the CBT and SBT treatments compared to the NBT treatment (Table 2), and this might increase the chance of the two metals in porewater immobilized by microbes, particularly for Cr, which occurred mainly as soluble CrO_4^{2-} at neutral pH or alkaline conditions (Table 2) (Novotnik et al., 2014; Pan et al., 2014).

In contrast with Cr and Cd, Cu, Ni and Mn levels in decomposing litters generally decreased with increasing burial depth (Fig. 4). There were two possible reasons. First, with increasing burial depth, the anoxic conditions formed in deep layers generally caused the sulfate (SO_4^{2-}) in porewater to be reduced to dissolved sulfides, which could effectively sequestrate many heavy metals such as Pb, Cr, Cu, Zn, Ni, Mn, Cd, Co and V. Because the SO_4^{2-} levels in salt marsh of the Yellow River Estuary were very high (0.11%–0.21%) (Fan et al., 2010), the sulfate dissimilation and the reactions between sulfides and metal ions might occur actively (Weber et al., 2009; Sun et al., 2014). As a result, the metal sulfides formed in sediments showed low solubility and mobility. Although this mechanism could reduce the chance of some metals (e.g., Cr, Cu, Ni and Cd) in porewater

Table 4 Correlation coefficients between metal concentrations and metal/carbon (M/C) ratios or carbon/nitrogen (C/N) ratios

Burial treatments	Ratios	Pb	Cr	Cu	Zn	Ni	Mn	Cd	V	Co
NBT	M/C	0.992**	0.993**	0.995**	0.992**	0.988**	0.997**	0.997**	0.993**	0.990**
	C/N	0.034	0.183	–0.849**	–0.465	–0.477	–0.074	–0.528	0.301	–0.399
CBT	M/C	0.989**	0.997**	0.998**	0.996**	0.982**	0.993**	0.998**	0.981**	0.983**
	C/N	–0.298	0.301	–0.981**	–0.551	–0.786**	0.156	–0.678*	–0.050	–0.160
SBT	M/C	0.996**	0.996**	0.998**	0.999**	0.997**	0.991**	0.998**	0.986**	0.992**
	C/N	–0.427	–0.118	–0.952**	–0.271	–0.719*	–0.339	–0.690*	–0.538	–0.536

Notes: NBT, no burial treatment; CBT, current burial treatment; and SBT, strong burial treatment. * Correlation is significant at the 0.05 level; and ** Correlation is significant at the 0.01 level.

immobilized by microbes, it might be unimportant for Cr and Cd since the two metal concentrations in decomposing litters generally increased with increasing burial depth as mentioned above. By comparison, it might be one of important mechanisms inducing the concentrations of Cu and Ni to be decreased with increasing burial depth. Second, with increasing burial depth, Mn behavior influenced by organic matter degradation might be changed greatly. The oxidation of organic matter might lead to the use of Mn-oxide (MnO_2) as electron acceptor and the reduced Mn form (Mn(II)) might leach from decomposing litters (Pereira et al., 2007). Previous studies have reported that the Mn concentration in sediments of the Yellow River Estuary was relative high and the value varied between 305.87 and 711.39 mg/kg (Sun et al., 2013), indicating that Mn leaching might be enhanced as the Mn-oxide was substantially reduced. In this investigation, sediment moisture generally increased with increasing burial depth (Table 2), and this might induce Mn leaching from decomposing litters to be increased simultaneously. Moreover, under anoxic conditions, as Mn-oxide was completely reduced to Mn(II), the Mn(II) usually precipitated as rhodochrosite ($MnCO_3$) (Lovley and Phillips, 1988), which might result in the decrease of Mn levels in porewater immobilized by microbes.

The investigation showed that, in most sampling periods, Pb, Cr, Zn, Ni, Mn, V and Co stocks in *S. glauca* in the three burial treatments were lower than the initial ones, indicating that, over 571 d of decomposition, release generally exceeded incorporation (Fig. 5). Although the export amounts of the seven metals increased greatly with increasing burial depth, the export between sampling periods was not uniform (Fig. 6). In the CBT and SBT treatments, stocks of Cd in *S. glauca* were generally positive, evidencing incorporation of the metal in most sampling periods. The investigation also indicated that, with increasing burial depth, stocks of Cu in *S. glauca* shifted from release to accumulation in most times, and, particularly, the incorporation of Cu occurred in the SBT treatment (Fig. 6). Similar results were reported by Windham et al. (2004) and Pereira et al. (2007) who also found Cu enrichment in litters as decomposition proceeded. Thus, the *S. glauca* acted as cation exchanger absorbing Cu from sediments or seawater and the strong affinity of Cu to organic matter might promote this sorption (Stumm and Morgan, 1996). Overall, the *S. glauca* were particular efficient in binding Cd and releasing Pb, Cr, Zn, Ni, Mn, V and Co, and, with increasing burial depth, stocks of Cu in decomposing litters shifted from release to accumulation, implying that the eco-toxic risk of Pb, Cr, Zn, Ni, Mn, V and Co exposure would be serious as the strong burial episodes occurred in *S. glauca* marsh in future.

4.3 Uncertainties and future works

Although this study was based on determinations at three sub-plots, the results of this experiment were still very important in evaluating the stocks of nutrients (C, N) and metals (Pb, Cr, Cu, Zn, Ni, Mn, Cd, V and Co) in decomposing litters of *S. glauca* as affected by different episodic depositions. However, two uncertainties should be emphasized: 1) at the end of decomposition, the percent of mass remaining and the $t_{0.95}$ in the NBT, CBT and SBT treatments were 23.00%, 23.17%, 23.42% and 3.65, 3.12 and 3.42 yr, respectively, indicating that, as the *S. glauca* litters in different treatments decomposed completely, a very long time was needed and the conclusions derived from this study only reflected the variations of nutrients and metals in decomposing litters in a short-term scale. Next step, to precisely assess the mass balance of these nutrients and metals in decomposing litters, long-term decomposition experiment should be further conducted. 2) under episodic deposition, the spatial heterogeneity of abiotic and biotic factors in *S. glauca* distribution area also showed great influences on litter decomposition and nutrient/metal stocks in decomposing litters. Therefore, to accurately evaluate the mass balance of these nutrients and metals in decomposing litters of *S. glauca* in intertidal zone as affected by episodic deposition, more site-level decomposition experiments should be conducted. In addition, as the data were enlarged from site-level to regional-level, the scale conversion should be carried out based on the data obtained from long-term site-level studies.

5 Conclusions

This paper investigated the potential influences of episodic deposition on nutrient and heavy metal variations in decomposing litters of *Suaeda glauca*. Results have demonstrated that: 1) the decomposition rates of *S. glauca* in different burial treatments generally followed the sequence of

CBT > SBT > NBT ($P > 0.05$). 2) Except for Mn, no significant differences in C, N, Pb, Cr, Cu, Zn, Ni, V and Co concentrations occurred among the three treatments ($P > 0.05$). With increasing burial depth, Cr and Cd levels generally increased while Cu, Ni and Mn concentrations decreased. 3) Episodic deposition was generally favorable for C and N release from *S. glauca*. Stocks of Pb, Cr, Zn, Ni, Mn, V and Co in *S. glauca* of the three burial treatments generally evidenced the export of metals from litter to environment, and the export amounts increased greatly with increasing burial depth. And 4) the *S. glauca* were particular efficient in binding Cd and releasing Pb, Cr, Zn, Ni, Mn, V and Co, and, with increasing burial depth, stocks of Cu in decomposing litters generally shifted from release to accumulation. This study found that the potential eco-toxic risk of Pb, Cr, Zn, Ni, Mn, V and Co exposure would be serious as the strong burial episodes occurred in *S. glauca* marsh. Next step, to accurately evaluate the mass balance of these nutrients and metals in decomposing litters of *S. glauca* as affected by different episodic burials, the site-level measurements should be designed at fine scales and the time-scale of decomposition experiment should be extended.

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